Solid-State Optical Cooler Developments

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ABSTRACT

Optical cooling of solids was first demonstrated in 1995. Since that time our efforts have concentrated on using this phenomenon to produce a viable optical cryocooler. A bench-top, solid-state optical cooler was demonstrated recently with 54 °C of cooling from room temperature and a heat lift of 25 mW when it was pumped with 1.6 watts of laser light. Based on the bench-top cooler results a compact, rugged, self-contained system with laser-diode pumping is being constructed as a prototype for research and commercial applications. Recent results, designs and plans for future work are discussed.

In addition to prototype work, our efforts have continued on producing additional optical materials which demonstrate optical cooling and will improve the efficiency and useful temperature range of optical coolers. New materials with promising results are discussed.

INTRODUCTION

The basic principles for optical refrigeration, cooling by anti-Stokes fluorescence were first discussed in 1929[1]. Much more recently, optical refrigeration has been demonstrated experimentally with ytterbium doped fluoride glass, Yb:ZBLAN,[2, 3, 4] and in laser dye solutions[5, 6]. Since these first demonstrations several studies have investigated materials for their potential in optical refrigeration[7, 8]. Two independent, theoretical studies found that Yb:ZBLAN could be used as the working material in an optical refrigerator that operates below 80K with efficiencies comparable to those of small mechanical cryocoolers[9, 10]. Optical refrigerators such as these would be valuable for many low-power cooling applications including cooling radiation detectors, high-temperature superconductors and electronics. Since optical refrigerators are solid-state devices without any moving parts or thermal connections between the cold and warm stages, other than structural supports, they would be free of vibrations, mechanically robust, reliable and represent a new approach to cryogenic refrigeration.

The basic principle of optical cooling involves pumping an optical solid with light that is absorbed, effectively combined with thermal energy and re-radiated. This process removes energy or heat from the material. In our system the Yb ions in our glass have a ground state manifold and effectively only one excited-state manifold. When the Yb-doped material is pumped at wavelengths longer than the mean fluorescence, ions are excited from the higher energies of the ground state manifold to the lower energies of the first excited manifold. The system returns to thermal equilibrium by absorbing phonons and then radiates a photon. On the average this radiated photon will have a higher energy than the pump photons. The difference in the photon energies is heat removed from the optical material.

The first stage of research on laser cooling in solids and liquids was theoretical. The second stage has been the experimental demonstration of the principle. The third stage we

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believe will be the practical application of this process. To compete with highly developed cryocooler technologies an optical cryocooler must be demonstrated to have comparable performance, distinct advantages in some areas and it must be inexpensive to manufacture. Our efforts at Los Alamos National Laboratory since the initial laboratory demonstration have been directed toward answering these practical application questions.

At the end of 1999 the results of a bench-top cooler were published[11] which laid the ground work for production of a self-contained prototype. The bench-top cooler implemented many of the aspects of a practical cryocooler and provided valuable information on what studies still needed to be completed before a commercial production program could be implemented.

EXPERIMENT

The research on optical cooling in solids at Los Alamos National Laboratory has focused on two areas. The first is construction of a prototype cryocooler utilizing optical cooling. The second is searching for new materials that exhibit optical cooling.

Recent bench-top cooler experiments have demonstrated a 54°C temperature drop from room temperature (achieved with improvements on experiment in reference 11). These tests were done with an Argon ion-pumped Ti:Sapphire laser producing 1.6 Watts of pump power for the cooler. These experiments were completed inside a standard vacuum chamber with external optics, optical fiber supports and no cold finger. The next step is the construction of a self-contained system that can be used as a design testbed for a commercial cryocooler.

The prototype cryocooler under construction is shown in figure 1. This design was based on the bench-top system with modifications to the structural support, optical coupling for the pump light, cold finger and vacuum system. In the prototype the cooling material, coldfinger and support structures are enclosed in a small vacuum that is pumped out through a port on the end flange.

The mechanical support structure is based on a dewer design that utilizes coaxial G-10 tubes coupled on the ends. This design allows for a very stiff structure while limiting the thermal conductive load. In the current design the tubes each have 76 microns thick walls and are approximately 1.9 cm long with inside diameters of 1.55, 1.75 and 1.98 cm. Using a thermal conductivity for G-10 of 0.0028 W/cm/°C we find that for a temperature difference of 200° C there will be a thermal load from conduction of 8 mW. The internal walls of the vacuum will be

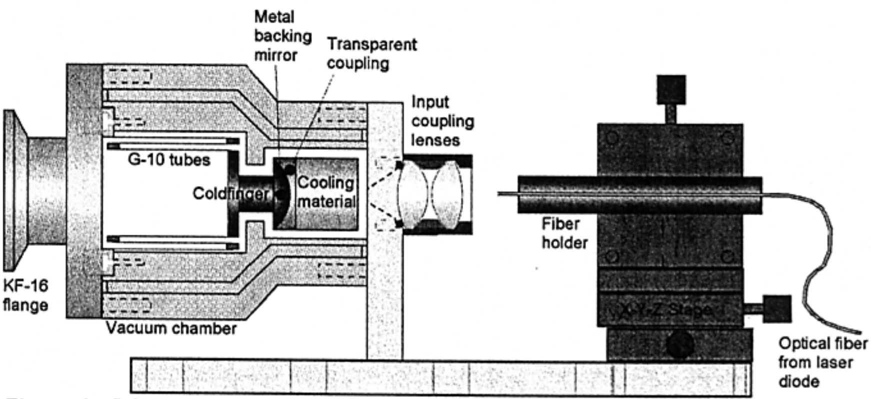

Figure 1: Schematic of the prototype cryocooler currently under construction at Los Alamos National Laboratory. The input laser comes in through the optical fiber on the right side of the figure. The pump light is focused by the lens coupling through a hole in the mirror on the Yb:ZBLANP cooling element. The cooling element, transparent coupling, coldfinger and part of the support tubes cool down. A vacuum is held between the leftmost coupling lens and the rightmost flange in the figure. The object to be cooled will be located inside the G-10 tubes and attached to the left end of the coldfinger.

coated with layers that have low emissivity at thermal wavelengths (0.02 and 0.05). The cooling element, transparent coupler, coldfinger and G-10 tubes can be assumed to be blackbody absorbers in the worse case. Accounting for the geometry of the system the calculated radiative thermal load is approximately 100 mW for a 200° C temperature difference. The total thermal load on the cold components should be less than 108 mW for a 200°C temperature drop in the cooling element.

Optical Coupling

The optical coupling design was tested and found to have a 86% throughput from coupling into the fiber to light through a 600 micron hole at the location of the cooling element. This spot size matches the hole size in the mirror of the cooling element. The lenses are made of sapphire and thermally sunk to the outer chamber.

Coldfinger/Cooling Element Coupling

The coldfinger and its coupling to the cooling element are designed to minimize the parasitic heating due to pump laser leakage and fluorescent light leakage as well as provide a highly conductive thermal link between the cooling element and the coldfinger. The coldfinger is made from aluminum, the transparent coupler is made of sapphire and the cooling element is Yb:ZBLANP with dielectric coatings on the ends. The materials for the coldfinger and coupler were chosen for their various thermal properties but the coupler may be made from ZBLANP in the future because of thermal expansion issues. The coldfinger and coupler will be mounted together with thermally conducting epoxy (the coupler will have a silver mirror coating on this surface) and the coupler and cooling element will be joined with < 2 microns of optical epoxy. When pumped in a vacuum with 1.5 W of laser power at Yb fluorescence wavelengths, the coupler / cooling element interface design did not change in temperature. This interface does however show mechanical problems when subjected to rapid temperature changes due to the thermal expansion differences between ZBLANP and sapphire. The coupler material may be changed to ZBLANP to overcome this thermal problem. This three element heart of the cooler should allow for good performance of the cooling element, a good thermal connection to the object to be cooled and eliminate any stray light escaping from the cooling element through the dielectric mirror.

Current Status

To date the lens coupling, cooling element and transparent coupler are in hand. The vacuum chamber, support structures and coldfinger are expected to be complete by the end of June, 2000. The 15 W diode pump lasers we will be using for this experiment have been tested, found to a thermal problem and are currently being repaired.
A full-up prototype test is expected to occur in July.

New cooling materials

In parallel we have been studying new materials that may exhibit cooling. Recently two new materials have been found to cool when pumped with the proper wavelength of light. The first is Yb:YAG and the second is Tm: ZBLANP.

One material recently found to cool is Yb:YAG (fig. 2). The Yb:YAG was pumped at wavelengths from 990 nm to 1050 nm and found to cool 0.36°C at 1030 nm with approximately 10 mW of absorbed pump power. The full results of these experiments have been submitted for publication. The advantages of a Yb:YAG over Yb:ZBLANP include: 1) possible higher efficiency at lower temperatures due to the narrower lines in the YAG, 2) improved cooler performance due to higher thermal conductivity of YAG, 3) better mechanical stability of YAG, and 4) better substrate for

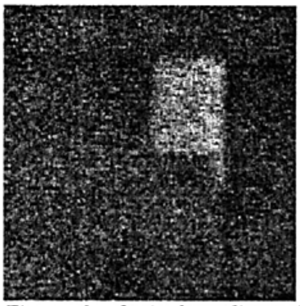

Figure 2: Optical cooling of Yb:YAG. The white square is the Yb:YAG, below it is the reference glass sample. White objects are cooler in this image.

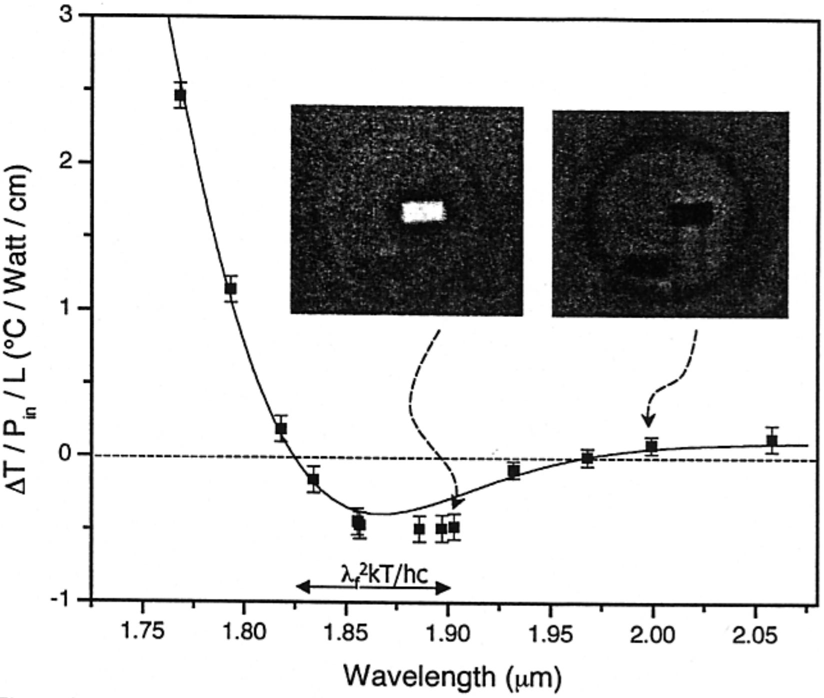

Figure 3:Temperature change, normalized to incident power, verses pump wavelength for a Tm:ZBLANP sample. The insets are two thermal images corresponding to 1.9 mm (cooling) and 2.0 mm (heating). The solid line is a theoretical model fit to the data.

dielectric mirror deposition.

We have also obtained a 1 cm block of Tm:ZBLANP and pumped it at wavelengths between 1.75 and 2.05 microns (fig. 3). The Tm:ZBLANP cooled 1.2°C with approximately 90 mW of absorbed pump power. These results were obtained by viewing the Tm:ZBLANP with a thermal infrared camera and comparing it to a reference ZBLANP block. Ignoring laser efficiencies, a cooler constructed with thulium as the active ion instead of ytterbium would be twice as efficient. The reason for the higher efficiency is that the input photons have one half the energy for the thulium system as compared to the ytterbium system but each photon can remove the same amount of energy. The current difficulty with implementing a thulium-based system is the availability of high-efficiency 2 micron diode lasers.

In addition we have begun studies of cooling in semiconductors. Semiconductors have been discussed as optical cooling materials[12, 13] and examined experimentally [14, 15] but no net cooling has been observed. The difficulty in achieving bulk cooling in a semiconductor and with implementing a semiconductor cooling element in a system has been the high index of refraction in the materials that trap the fluorescence and eventually produces net heating. This is not a trivial problem and our work is just beginning on how to get past this hurdle.

CONCLUSION

Optical cooling is solids has become accepted as demonstrated experimentally. The next step is to implement this laboratory effect in a practical system. Our program at Los Alamos National Laboratory is pushing toward a demonstration cryocooler which could prove the commercial feasibility of an optical cryocooler. The prototype is under construction and expected to be tested in the near future. In addition, one of the best ways to improve the efficiency of an optical cryocooler is with a cooling material with better performance characteristics. We have demonstrated cooling in two new materials, Yb:YAG and Tm:ZBLANP, that show promise for better performance in a cyrocooler system.

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